DECISION SUPPORT MODEL FOR MUNICIPAL
SOLID WASTE MANAGEMENT AT
DEPARTMENT OF DEFENSE INSTALLATIONS

THESIS

John F. Muratore, Captain, USAF

AFIT/GEE/ENS/95D-07

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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John F. Muratore, B.S.

Captain, USAF

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Committee:		Signature
Advisor	Jack M. Kloeber, Lt Col, USA Department of Operational Sciences	
Reader	Thomas R. Hauser Department of Engineering and Environmental Management	11/30/95
Reader	Wm. Brent Nixon, Major, USAF Department of Engineering and Environmental Management	

Preface

The purpose of this study was to develop a decision support model to aid Department of Defense installations in managing their municipal solid waste.

Although information from Wright-Patterson AFB was used in developing the model, the decision support model is not limited to use at Wright-Patterson AFB. The model can be used to evaluate solid waste management strategies at all Department of Defense installations.

This research effort would not have been possible without the contribution and support of many individuals. I would like to express special thanks to Lieutenant Colonel Jack Kloeber whose patience and willing assistance made this an outstanding learning experience. In addition, I would like to thank my committee members, Dr. Thomas Hauser and Major Brent Nixon. Finally, I thank Mom, Dad, and Lisa for their encouragement and support in making this endeavor possible.

John F. Muratore

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Abstract

This research focuses on the development of a decision support model to identify the preferred strategy for managing municipal solid waste using the principles of decision analysis theory. The model provides an effective decision making tool to evaluate and compare different municipal solid waste management strategies.

The users of this model, the Environmental Manager or decision maker at a given installation, can enter installation-specific waste stream characteristics, treatment and disposal costs, and material buy-back prices to determine the expected value for various alternative strategies. The strategy having the greatest expected value is considered the preferred alternative. In calculating the expected value of a strategy, the economic cost, social cost, and waste diversion from the landfill are evaluated.

This research also includes a representative case study to illustrate the use of the decision support model. Although the case study addresses Wright-Patterson AFB, the model can be applied to any Department of Defense Installation.

DECISION SUPPORT MODEL FOR MUNICIPAL SOLID WASTE MANAGEMENT AT DEPARTMENT OF DEFENSE INSTALLATIONS

I. Introduction

Background

Americans today generate over 200 million tons of municipal solid waste (MSW) each year (USEPA, 1994a:ES-3). That is nearly a 4.4 pounds per person per day, and the amount continues to increase (USEPA, 1994a:ES-3).

Since its beginnings in 1970, the United States Environmental Protection Agency has addressed many environmental problems including hazardous waste, air pollution, and water pollution. There is one problem that is faced by everyone, every day, and that is solid waste. Where does it come from, and where does it go? Those are two very intriguing questions because the origin of waste often determines its final destination.

Through the 1960's and 1970's, landfilling came to be the primary solution to the solid waste management problem. By the mid 1980's, 10 percent of MSW was being recycled and another 10 to 15 percent was being incinerated (Office of Technology Assessment, 1989:3). The remaining 75 to 80

percent was disposed of in landfills (Office of Technology Assessment, 1989:3).

The problem with continuing on in this manner is that citizens do not want the human health risks associated with either incinerators or landfills. Other alternatives are available, and they must be evaluated. Federal facilities must develop pollution prevention strategies that emphasize source reduction as the primary method of environmental protection (USEPA, 1994c:12). Landfill disposal should only be employed as a last resort (USEPA, 1994c:13).

Landfilling is rapidly becoming an expensive solution to the solid waste problem. This is due primarily to limited landfill capacity and the difficulty in siting new facilities. Landfill capacity is limited for three reasons: older landfills are reaching the end of their life expectancies, unsafe landfills are closing due to increased regulation, and new landfills are not being sited due to strong opposition from the public (Office of Technology Assessment, 1989:3). In one survey, EPA indicated that about one third of the existing landfills were expected to close by 1994 and 80 percent of the landfills operating in 1988 will close in the next 20 years (Office of Technology

Assessment, 1989:271). Nine hundred landfills were closed in 1993 due to stiffer regulations (Steuteville, 1994b:46).

Landfilling is becoming expensive due to the difficulty in siting new facilities. Concerns over past practices conducted with few pollution controls make the public reluctant to accept any new landfills. Opposition to these sanitary landfills, even with their synthetic and clay liners, leachate and gas detection and collection systems, and final cover systems remains strong (Office of Technology Assessment, 1989:272). The resistance is due to the public's perception of human and ecological risk and fear of diminished property values.

Landfills, however, are not the only alternative for solid waste disposal. Incineration, mentioned earlier, is a common, though similarly unpopular, alternative for reducing our dependence on landfills. Recycling and composting are two other alternatives. Finally, instead of focusing on the garbage after it is generated, another alternative is to reduce the amount of waste generated. This is known as pollution prevention and source reduction. For Department of Defense installations, the solid waste disposal decision may involve any or all of these five alternatives:

landfilling, incineration, recycling, composting, and source reduction.

The Federal Pollution Prevention Act of 1990 established the waste management hierarchy of reducing pollution at the source first. Pollution that cannot be **reduced** should be **recycled**. **Treating** pollution that cannot be prevented or recycled is the next step, and **release** into the environment such as in a landfill or incineration, should only be used as a last resort (USEPA, 1994c:12-13).

The solid waste management strategy depends on the waste stream at the installation, the economic and social costs for the different alternatives, the pollution prevention hierarchy, and the preferences of the decision makers.

Research Problem

The Department of Defense needs a decision model that installations can use in managing their solid waste. The model should assist the decision maker in choosing the most effective strategy for managing the municipal solid waste. Four criteria - the attainment of pollution prevention goals, the waste diversion from landfills, the economic

cost, and the social cost - should be addressed by the model and used in the selection process.

Research Objective

The purpose of this research is to develop a multicriteria decision support model that DOD installations can use in managing the solid waste they generate.

Supporting Objectives

1) Model the values, uncertainties, decisions, and influences involved in the solid waste decision making process.

2) Use valid data from Wright-Patterson AFB to demonstrate how an installation solid waste manager would use the model to generate a solid waste strategy.

Scope Limitation

The selection of a solid waste management strategy is a complex task. This research effort will focus only on municipal solid wastes typically found at DOD installations such as paper products, aluminum cans, glass, plastics, yard and food wastes generated on base and in base housing. Since this research focuses on municipal solid waste, the

disposal of hospital waste and industrial waste will not be addressed. Incinerator ash, however, will be addressed since it results directly from the incineration of municipal solid waste. Using decision analysis techniques, this project will develop a model for choosing the most effective solid waste management strategy given the information available at a specific DOD installation.

Organization of the Research Report

The first step in developing an appropriate multicriteria decision support model for solid waste management is to fully comprehend the broad scope of the solid waste management problem. Chapter Two, the Literature Review, will address the current strategies for solid waste management as well as current modeling of the problem. In addition, economic costs for the alternatives will be presented along with a discussion of the Pollution Prevention Act. Following the Literature Review, Chapter 3 will discuss multicriteria decision making techniques along with the methodology used in developing the model. The overall value function will be discussed and the model itself will be presented. Chapter 4 will introduce data from the Wright-Patterson AFB solid waste survey. The model

developed in Chapter 3 will be used to analyze this data and produce a recommended strategy. A sensitivity analysis will be performed and a summary of findings will be included. Conclusions will be presented in Chapter 5 along with recommendations for further study.

II. Literature Review

This chapter presents a review of some of the literature applicable to the management of municipal solid waste (MSW). First, the available disposal alternatives will be discussed along with their economic costs. Current modeling of the problem will be presented along with a discussion of the Pollution Prevention Act. Finally, social costs will be addressed.

Terms such as trash, garbage, refuse and waste are thought to be synonymous. The U.S. Environmental Protection Agency defines municipal solid waste as: non-hazardous waste generated in households, commercial and business establishments, institutions, and light industrial process wastes, agricultural wastes, mining wastes, and sewage sludge (Office of Technology Assessment, 1989:3).

Alternatives

Landfilling. Landfilling solid waste is probably the oldest disposal method, growing from open or burning dumps to sanitary (earth-covered) landfills as concerns about health effects increased (Liptak, 1991:23). Landfilling

today, according to the Office of Technology Assessment, is disposing of waste on land in a series of compacted layers and covering it, usually daily, with soil or other materials such as compost (Office of Technology Assessment, 1989:271).

Landfilling is the primary method for managing solid waste in the United States today and will continue to be needed to manage nonrecyclable, noncombustible materials as well as incinerator ash (Office of Technology Assessment, 1989:27). Only a few Air Force bases continue to operate their own sanitary landfills. At most bases, refuse collection is now performed by service contracts, and the disposal is at a commercial or municipal facility (AFCEE, 1994:3-18). In this sense, DOD installations are at the mercy of the refuse contractors and local solid waste authorities. The installations generate the waste and must depend on private contractors to remove and dispose of it.

Incineration. People have burned garbage for centuries, but uncontrolled burning of MSW has been banned in the U.S. since the Clean Air Act of 1970 (Office of Technology Assessment, 1989:217). Today there are 130 heat recovery and 50 regular incinerators in operation in the

United States (Liptak, 1991:87). Because matter is indestructible, incineration does not eliminate waste. It merely changes its form and volume (Liptak, 1991:88).

Incineration is not considered a waste disposal method but rather a waste processing technology (Denison and Ruston, 1990:172). Incineration reduces the volume of the waste requiring disposal, but generates ash which must be disposed. The amount of ash remaining depends on the refuse burned, and may range from 5 to 15% by volume or 20 to 30% by weight (Liptak, 1991:95). When unseparated MSW is "mass burned," the residue is typically 25% by weight (10% by volume). If only the combustible portion of the MSW is burned, the residue is half as much (Liptak, 1991:27). This means when the MSW is separated and only the combustible portion is burned, less ash remains, but the uncombustible portion of MSW must also be disposed.

The ash from incinerators has been found to contain high levels of several toxic metals and can also contain dangerous levels of organic compounds, such as dioxins (Denison and Ruston, 1990:177). Ash can be dispersed more readily through the environment compared to unburned solid waste. This leads to a greater exposure to the toxins

(Denison and Ruston, 1990:177). Ash can be inhaled or ingested more readily thus providing several new pathways for exposure (Denison and Ruston, 1990:177). Ironically, more efficient air pollution control devices result in ash containing even higher levels of toxic substances (Denison and Ruston, 1990:177).

Opponents of incineration point to the health hazards, the noise and odor, the increase in truck traffic, and the potential for air, land, and water pollution (Liptak, 1991:87). Incineration used to be inexpensive, but now with better material recovery, complete combustion at higher temperatures, scrubbers, and bag filters, the costs have increased substantially (Liptak, 1991:91). Wet scrubbers collect particulate matter by impaction with water droplets (Griffin, 1994:198). Baghouses or fabric filters also control particulate matter. The fabric provides support for a thin layer of particles known as pre-coat. This pre-coat then forms a filter cake on the surface of the fabric (Griffin, 1994:195-196).

In the 1960's, the cost of incinerating a ton of solid waste, not including capital costs, was around $5 and by 1977, the average cost was $26. In the Northeast, the

average tipping fee was $40 per ton in 1987, and by 1991 this had doubled (Liptak, 1991:15). The capital costs for incinerators approached $133,000 per TPD (ton per day) of capacity in 1990 (Liptak, 1991:91).

Incineration does not offer a complete solution to solid waste disposal because the process generates ash, which must be landfilled. In addition, not everything can be incinerated. Incineration does, however, provide a means of extending the life of existing landfills.

Another advantage of incineration is the energy recovery system that converts the released heat into steam and subsequently into electricity. The steam and electricity from a waste-to-energy incinerator provide a source of revenue to partially offset the costs of the incinerator. At the same time, a waste-to-energy incinerator reduces the demand for the current power generation method. The end result is less pollution is produced.

Recycling. In contrast to incineration, recycling is the process by which materials destined for disposal are collected, reprocessed or remanufactured, and reused (USEPA,

1994c:13). On-site recycling is defined as reusing the waste as a raw material in another process. An example of this would be using the dirty solvent from cleaning electrical components to clean tools or machinery. Off-site recycling is resource recovery where the raw materials are re-used. One example is the turning of used plastic soda bottles into new lawn furniture.

The collection, source separation, and processing necessary for a full-scale recycling program can be adapted to the specific situation. Different options include voluntary programs like drop-off centers, buyback/processing centers, commercial recycling programs for offices, and residential curbside collection. In addition, these programs can be made mandatory by imposing fines or refusing to pick up garbage that has not been separated. Another option is to collect the garbage and then separate recyclables from non-recyclables. This minimizes the amount of recyclable material being landfilled, but may be costly to operate.

The costs for a recycling program vary widely depending on the size and location. A good estimate is from $50,000 to $100,000 for capital costs for a 12,000 ton per year

operation (Institute for Local Self-Reliance, 1991:49). Operations and maintenance costs can range from $25 to $50 per ton (Institute for Local Self-Reliance, 1991:53).

The most frequently reported estimate for the national solid waste recycling rate is 10 percent of all MSW(Office of Technology Assessment, 1989:135). The Air Force recycled 11 percent of its solid waste in 1992 (AFCEE, 1994:3-18). Recycling does not completely eliminate the need for landfilling, but reduces the volume sent to the landfill. The recyclable portion of solid waste can approach 75% by weight if it is separated (Liptak, 1991:303).

Another critical element in recycling is the market for recycled materials. Maintaining a demand for recycled materials requires cooperation between government, industry and the public. Well-coordinated legislation can not only motivate recycling but can also improve the market for the recycled goods.

DOD installations face a number of options when it comes to recycling. A voluntary drop-off program can raise funds for recreation activities and reduce landfill costs. A voluntary curbside recycling program may generate revenue and could also reduce dependence on landfills. Finally, a

mandatory recycling program may greatly reduce the solid waste volume and thus the disposal costs for the installation.

<u>Composting.</u> Composting refers to the biological decomposition of solid organic materials into a stabilized humus. Composting yard waste results in a product that can be used again as ground cover, topsoil or fertilizer. Composting has been around for years but is now seen as a method of diverting materials from landfills. Composting reduces the volume of the original material from 50 to 80 percent. It is estimated that as much as 60 percent of the nation's garbage may be compostable (Merrymon, 1993:10). This estimate includes yard waste and paper waste.

Yard waste such as leaves, tree trimmings, and grass account for about 20 percent of the solid waste stream (AFCEE, 1994:3-20). On DOD installations, yard waste is generated from grounds maintenance, tree trimming contracts, and yard maintenance on golf courses and in military family housing (AFCEE, 1994:3-18).

Cost estimates for a typical composting program vary widely, but one source estimates capital costs to be from

$50,000 to $200,000 for a 12,000 ton per year operation (Institute for Local Self-Reliance, 1991:49). Operations and maintenance costs may range from $20 to $40 per ton (Institute for Local Self-Reliance, 1991:53).

Like recycling, composting may involve a separate collection. Yard wastes kept separate from other solid waste components can be handled and composted easily, but a separate collection is costly. Yard wastes can be left mixed with other wastes, but this requires costly mechanical equipment to do the separating. Air Force installations, such as Seymour Johnson AFB, have begun to divert yard waste into composting operations on base (AFCEE, 1994:3-18). Seymour Johnson AFB processed over 1 million pounds of yard waste in the first six months of 1993. Their composting program saves $62,000 annually in disposal costs(AFCESA, 1994:A-3).

Another advantage of composting, aside from avoiding the landfill costs, is the potential economic savings from avoiding fertilizer and topsoil purchases. Seymour Johnson AFB saves $3,800 annually in fertilizer purchases and $10,600 annually in topsoil purchases (AFCESA, 1994:A-3).

The odor from composting may be a problem, but this can be controlled through proper temperature controls and agitation. The preferred site for a composting plant is a rural agricultural area at least half a mile from built up areas (AFCEE, 1994:3-18). This could present a challenge for many DOD installations.

Source Reduction. Source reduction, as defined under the Pollution Prevention Act, refers to any practice that reduces the amount of any hazardous substance, pollutant or contaminant entering any waste stream or otherwise released into the environment prior to recycling, treatment, or disposal (USEPA, 1994c:13). Source reduction includes equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control.

Source reduction provides a relatively inexpensive way of reducing an installation's solid waste disposal problem. Source reduction requires a cultural change, a change in attitude. The United States Postal Service identified the following as ways to achieve source reduction: using old

drafts for scrap or notepads, expanding use of voice mail, and procuring durable instead of disposable items (USEPA, 1994c:27).

Department of Defense installations can put limits on the amount of copier paper available to reduce the number of copies made. Another idea is to use both sides of the paper. Finally, by using electronic mail instead of hard copy letters, the amount of paper to be recycled or landfilled will be reduced.

Current Modeling

The solid waste management problem is being modeled with linear programming techniques, least-cost scheduling, grey dynamic programming and numerous computer models.

Hsin-Neng Hsieh and Kuo-hua Ho developed a mathematical model for a typical solid waste disposal system. Their model accounts for waste collection, transportation, and disposal costs (Hsieh, 1993:194). The linear programming scheme is solved by the least-cost method and can be applied to the optimal design of a waste treatment system. The approach assesses different disposal plans, minimizes total

cost, and addresses the impacts incineration and recycling have on landfill capacity.

Jay R. Lund developed a linear method for evaluating and scheduling a set of recycling efforts over time to minimize the net present value of landfill operation, closure, and replacement. The program yields a least-cost recycling plan, calculates landfill lifetime, and minimizes the present value cost of providing solid waste disposal services into the indefinite future (Lund, 1990:182). His relevant costs include the costs of recycling, landfill closure, landfill operation, and landfill replacement. The recycling options to be scheduled and evaluated are first formulated by the engineer and must be reasonable for the location (Lund, 1990:184).

Geo H. Huang uses "Grey Dynamic Programming for Waste Management Planning Under Uncertainty." Fuzzy Dynamic Programming (FDP) is usually designed to reflect trade-offs between optimization goals and constraints. Problems with the model include more complicated submodels that may be computationally difficult for practical applications (Huang, 1994:133). Stochastic Dynamic Programming (SDP) can effectively deal with various probabilistic uncertainties in

decision making, but the problem is that increased data requirements create difficulties in their application (Huang, 1994:133). Grey dynamic programming allows uncertain information to be directly communicated into the optimization process and solutions without encountering the potential problems of FDP and SDP (Huang, 1994:133). The GDP approach may be more advantageous than the FDP or SDP approaches because uncertainties are reflected while computational requirements are not significantly increased (Huang, 1994:152).

The article "Computer Models for Recycling and Solid Waste Management" discusses recycling and solid waste modeling. The computer programs share the same structure and inputs such as households served, waste generation rates, waste composition, diversion rates, and costs (Engel, 1990:38). Each model is unique in its level of complexity, input requirements and types of output generated (Engel, 1990:39).

Pollution Prevention Act

The Federal Pollution Prevention Act of 1990 provides the mandate for federal facilities to practice pollution

prevention (USEPA, 1994c:12-13). The Act states the following:

> The Congress hereby declares it to be the national policy of the United States that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner whenever feasible; pollution that cannot be prevented or recycled should be treated in an environmentally safe manner whenever feasible; and disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner.

The Pollution Prevention Act of 1990 (USEPA, 1994c:13) establishes the hierarchy of environmental risk reduction as:

1. Source Reduction
2. Recycling
3. Treatment
4. Disposal

<u>U.S. Air Force Pollution Prevention Policy.</u> The Air Force is committed to achieving the goals outlined in Air Force Instruction 32-7080, Pollution Prevention Program. The Air Force's pollution prevention program calls for reducing solid waste disposal 50% by 1997 based on a 1992 baseline. Interim objectives call for a 10% reduction by 1993 and a 30% reduction by 1996 (AFCEE, 1994:3-17). This strategy will be accomplished in two primary ways. First,

solid waste disposal will be reduced directly by reducing the amount of waste generated, i.e., source reduction. The second method is by indirectly reducing disposal through recycling and composting. A combination of these strategies will be necessary to achieve the 50% reduction objective.

The largest target for DOD installations appears to be paper. Paper, by weight, makes up over 40% of the national solid waste stream (USEPA, 1994a: ES-5). Preliminary characterizations of the solid waste stream at Air Force bases indicate the waste composition is somewhat higher than the national average for paper (AFCEE, 1994:3-19). Each installation must analyze its waste stream and determine the best opportunities and strategies for reduction (AFCEE, 1994:3-19).

Social Costs

In environmental analysis, some costs and benefits are ignored because they are much more difficult to measure than others (MacLean, 1986:43). The long-term environmental impacts of large projects are frequently cited as an example (MacLean, 1986:43). The economic costs and waste diversion amounts for different waste strategies can be quantified.

The social costs of landfilling, incineration, recycling, composting and source reduction are not as easily measured.

Although the models discussed above account for waste composition, waste diversion, economic costs, and uncertainties, none of the models addressed any aspect of social costs. Social costs will be accounted for in the model developed in this thesis.

III. Methodology

Introduction

With all the different possibilities for solid waste management, it is not obvious which strategy is the best. The best strategy for the solid waste stream will be determined by looking at four criteria: attainment of pollution prevention goals, waste diversion from landfills, reduction in economic cost, and social cost. The principles of decision analysis provide an effective method of analyzing these four criteria along with the effects of uncertainty (Clemen, 1991:2). This chapter presents the decision model used to evaluate and compare the various solid waste management alternatives. A discussion of the principles of decision analysis and the tools used to model the decision problem can be found in the Appendix.

Decomposing and Modeling the Problem

Structuring the Problem. The first step in the decision analysis process is to construct a model of the decision problem that identifies the elements affecting the final outcome and the relationship among those elements

(Clemen, 1991:34). This thesis will use an influence diagram to represent the elements of the decision and their relationships. The model structure is presented from the view point of the Environmental Manager (EM) who is responsible for the installation's solid waste management program.

The EM is concerned with managing the installation's solid waste for the least economic cost and the least social cost. In addition, the EM has pollution prevention goals to meet concerning solid waste disposal. Meeting the pollution prevention goals is good, but the more waste that is reduced, the better. The problem from the EM's viewpoint is which solid waste management strategy meets the pollution prevention goals and offers the greatest waste diversion at the minimum economic cost and minimum social cost. To determine which strategy presents the best value, the EM must determine which factors affect the waste diversion from the landfill and the costs along with the effect uncertainty has on the final outcomes.

Figure 1 shows the influence diagram for the solid waste management decision.

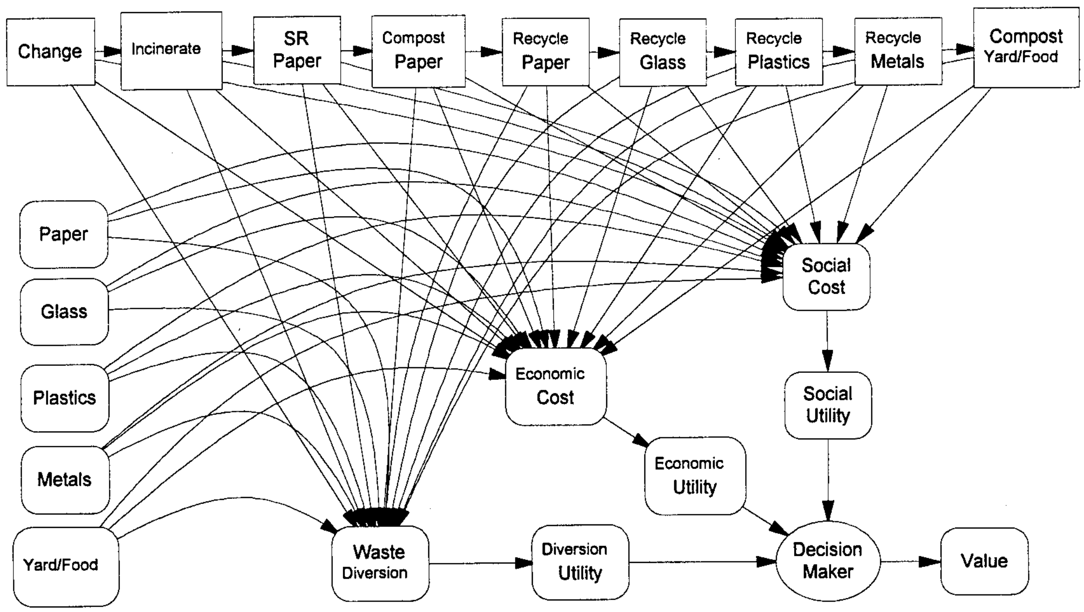

Figure 1. Influence Diagram.

<u>Decisions.</u> The first decision the EM must evaluate is whether to make a change from the current solid waste strategy, also known as the baseline. Figure 1 shows arcs leading from the **Change** decision to the value nodes **Economic Cost**, **Social Cost** and **Waste Diversion**. The EM will make a change from the baseline strategy only if an alternate strategy is available for less economic cost, less social cost or if it diverts more waste from the landfill than the baseline strategy. In this case, the values for not making a change are the current annual economic costs, social costs

and amount of waste being diverted from the landfill. If there is no alternative that costs less or diverts more waste from the landfill, the EM will remain with the baseline strategy.

If an alternative does exist that is better than the baseline strategy, the EM will evaluate the next decisions. The remaining decisions are only applicable if a change is to be made to the current solid waste strategy.

Incinerate is the next decision. In this model, incineration will only be used for paper, glass, metals and yard/food waste. Plastics will either be recycled or landfilled since they are a major contributor of both lead and cadmium to incinerator ash (Denison and Ruston, 1990:180). The EPA estimates 71% of the lead in air emissions and ash is contributed by plastics (Denison and Ruston, 1990:181). In addition, almost all (88%) of the cadmium comes from plastics (Denison and Ruston, 1990:181).

The decision here is what percentage of the paper, glass, metals, and yard/food waste to incinerate. Anywhere from none to 100% in increments of 10% is possible in the model.

To calculate the *Waste Diversion* for the incinerator, this model assumes unseparated MSW is mass-burned and the residue is 25% by weight (Liptak, 1991:27). For example, if 10,000 tons of MSW are incinerated, the residue is 2500 tons, and the waste diversion due to incineration is 7500 tons. The waste diversion from incineration will be included in the waste diversion equations for the five waste streams.

This model compares the annual economic costs of the waste management strategies. The *Economic Cost* for the decision to incinerate is equal to the incinerator tipping fee multiplied by the tons of MSW incinerated. The tipping fee includes the operations and maintenance costs as well as the cost of landfilling the incinerator ash. Equation 1 shows the *Economic Cost* for incineration where Incinerate is the percentage incinerated and Incineration Cost is the incinerator tipping fee in dollars per ton.

Economic Cost

Incinerate = (Incinerate)*(Paper + Glass + Metals + Yard/Food)*(Incineration Cost) (1)

The next sequence of decisions are based on the particular waste stream: paper, glass, plastics, metals, and yard/food waste.

Paper. The paper decisions are **SR(source reduce) Paper**, **Compost Paper**, and **Recycle Paper**. The source reduction, compost, and recycling decisions for paper choose the percentage of paper to be disposed of by each method. The decision is limited to 0 to 20% for source reduction since paper can only be reused as scrap paper so much. The decision ranges from 0 to 30% for recycling and composting. The largest recycling rate reported in Beyond 40 Percent was 35 percent, while the largest composting rate was 31 percent (Institute for Local Self-Reliance, 1991:15). The percentage remaining after diversion equals the amount to be landfilled.

In the event the **Incinerate** decision is chosen, constraints in the model prevent more than 100% of the paper from being diverted from the landfill. The value for *Waste Diversion* in this case is equal to the percentage diverted multiplied by the total amount of paper, as shown in

Equation 2.

$$\text{Waste Diversion Paper} = (\text{Source Reduction Paper} + \text{Compost Paper} + \text{Recycle Paper} + \text{Incinerate}*.75)*\text{Paper} \quad (2)$$

The *Economic Cost* for paper is equal to the percentage of paper diverted for each decision multiplied by the applicable cost multiplied by the amount of paper, plus the landfill disposal cost for the remaining paper. In addition, the costs are offset by paper recycling profits and savings from source reduction and composting. This is shown in Equation 3.

$$\begin{aligned}\text{Economic Cost Paper} = [&\text{Source Reduction Paper}*\text{Source Reduction Cost} + \text{Compost Paper}*\text{Compost Cost} \\ &+ \text{Recycle Paper}*\text{Recycle Cost} + (1 - \text{Source Reduction Paper} \\ &- \text{Compost Paper} - \text{Recycle Paper} - \text{Incinerate})*\text{Landfill Cost} \\ &- (\text{Source Reduction Paper}*\text{New Paper Price} + \text{Compost Paper}*\text{Compost Price} \\ &+ \text{Recycle Paper}*\text{Used Paper Price})]*\text{Paper} \quad (3)\end{aligned}$$

<u>Glass.</u> **Recycle Glass** is the next decision. The decision ranges from 0 to 30% since one source reported a 30% recycling rate as being achievable (Institute for Local Self-Reliance, 1991:15). The percentage remaining after

diversion equals the amount to be landfilled. The value for *Waste Diversion* in this case is equal to the percentage diverted multiplied by the total amount of glass, as shown in Equation 4.

$$\text{Waste Diversion Glass} = (\text{Recycle Glass} + \text{Incinerate}*.75)*\text{Glass} \quad (4)$$

The *Economic Cost* for glass is equal to the percentage of glass diverted for each decision multiplied by the applicable cost multiplied by the amount of glass, plus the landfill disposal cost for the remaining glass. The costs are offset by glass recycling profits. This is shown in Equation 5.

$$\text{Economic Cost Glass} = [\text{Recycle Glass}*\text{Recycle Cost} + (1 - \text{Recycle Glass} - \text{Incinerate})*\text{Landfill Cost} - \text{Recycle Glass}*\text{Glass Price}]*\text{Glass} \quad (5)$$

Plastics. **Recycle Plastics** is the next decision. The decision ranges from 0 to 30% since one source reported a 30% recycling rate as being achievable (Institute for Local Self-Reliance, 1991:15). The percentage remaining after recycling equals the amount to be landfilled. The value for *Waste Diversion* in this case is equal to the percentage of

plastics recycled multiplied by the total amount of plastics, as shown in Equation 6.

$$\text{Waste Diversion Plastics} = (\text{Recycle Plastics})*\text{Plastics} \tag{6}$$

The *Economic Cost* for plastics is equal to the percentage of plastics recycled multiplied by the recycling cost multiplied by the amount of plastics, plus the landfill disposal cost for the remaining plastics. Additionally, this cost is offset by plastics recycling profits. This is shown in Equation 7.

$$\begin{aligned}\text{Economic Cost Plastics} = [&\text{Recycle Plastics}*\text{Recycle Cost} + (1 - \text{Recycle Plastics})*\text{Landfill Cost} \\ &- \text{Recycle Plastics}*\text{Plastics Price}]*\text{Plastics}\end{aligned} \tag{7}$$

<u>Metals.</u> Metals here include everything from aluminum and steel cans and containers to scrap metal. **Recycle Metals** is the next decision. The decision ranges from 0 to 30% since one source reported a 30% recycling rate as being achievable (Institute for Local Self-Reliance, 1991:15). The percentage remaining after diversion equals the amount to be landfilled. The value for *Waste Diversion* in this

case is equal to the percentage diverted multiplied by the total amount of metals, as shown in Equation 8.

$$\text{Waste Diversion Metals} = (\text{Recycle Metals} + \text{Incinerate}*.75)*\text{Metals} \quad (8)$$

The *Economic Cost* for metals is equal to the percentage of metals diverted for each decision multiplied by the applicable cost multiplied by the amount of glass, plus the landfill disposal cost for the remaining metals. These costs are offset by metals recycling profits. This is shown in Equation 9.

$$\text{Economic Cost Metals} = [\text{Recycle Metals}*\text{Recycle Cost} + (1 - \text{Recycle Metals} - \text{Incinerate})*\text{Landfill Cost} - \text{Recycle Metals}*\text{Metals Price}]*\text{Metals} \quad (9)$$

Yard and Food Wastes. Second only to paper products, yard and food wastes make up the largest portion of the solid waste stream. **Compost Yard/Food** is the next decision. The decision ranges from 0 to 30% since one source reported a 30% composting rate as being achievable (Institute for Local Self-Reliance, 1991:15). Source reduction for yard waste is not considered in this model, but it could be easily added. The percentage remaining after composting equals the amount

to be landfilled. The value for *Waste Diversion* in this case is equal to the percentage composted multiplied by the total amount of yard/food waste, as shown in Equation 10.

$$\text{Waste Diversion Yard/Food} = (\text{Compost Yard/Food} + \text{Incinerate}*.75)*\text{Yard/Food} \tag{10}$$

The *Economic Cost* for yard/food waste is equal to the percentage diverted by composting multiplied by the amount of yard/food waste multiplied by the applicable cost, plus the landfill disposal cost for the remaining yard/food waste. These costs are offset by savings in purchases of compost and fertilizer. This is shown in Equation 11.

$$\begin{aligned}\text{Economic Cost Yard/Food} = [&\text{Compost Yard/Food}*\text{Compost Cost}\\ &+ (1 - \text{Compost Yard/Food} - \text{Incinerate})*\text{Landfill Cost}\\ &- \text{Compost Yard/Food}*\text{Compost Price}]*\text{Yard/Food}\end{aligned} \tag{11}$$

In addition to the annual costs identified above, if any decision to pursue composting or recycling is chosen, capital costs for composting and/or recycling will be incurred. In this model, these costs are annualized over 10 years at an interest rate of 10 percent. The model has the flexibility to evaluate the strategies at any interest rate.

The annual cost for recycling and composting programs are shown in Equations 12 and 13, where A/P calculates the annual payments given the present cost, time period, and interest rate.

$$\text{Economic Cost Composting} = \text{Composting Capital Cost } (A/P, 10, .1) \tag{12}$$

$$\text{Economic Cost Recycling} = \text{Recycling Capital Cost } (A/P, 10, .1) \tag{13}$$

Social Costs. Some environmental costs and benefits are ignored by others because they are difficult to quantify (MacLean, 1986:43). Rather than completely ignoring social costs, this model will attempt to base the social costs for the waste management strategies according to the Pollution Prevention Hierarchy (USEPA, 1994c:13). In other words, since source reduction and recycling are preferred to treatment and disposal (USEPA, 1994c:13), then source reduction and recycling would have a lower social cost than incineration and landfilling.

The **Social Cost** node captures the social costs for the decisions. In this model, Source Reduction is assigned a cost of 1, Composting a cost of 2, Recycling a cost of 3, Incineration a cost of 4, and Landfilling a cost of 5.

These social costs score Landfilling as five times more costly socially than source reduction. This cost ranking will most likely will depend on the decision maker's situation. Therefore, the social costs can be adjusted according to the decision maker's preference.

Equations 14 through 18 calculate the total *Social Cost* for paper, glass, plastics, metals, and yard/food waste respectively.

$$\text{Social Cost Paper} = [\text{Source Reduction Paper}*1 + \text{Compost Paper}*2 + \text{Recycle Paper}*3 + \text{Incinerate}*4 + (1 - \text{Source Reduction Paper} - \text{Compost Paper} - \text{Recycle Paper} - \text{Incinerate})*5]*\text{Paper} \quad (14)$$

$$\text{Social Cost Glass} = [\text{Recycle Glass}*3 + \text{Incinerate}*4 + (1 - \text{Recycle Glass} - \text{Incinerate})*5]*\text{Glass} \quad (15)$$

$$\text{Social Cost Plastics} = [\text{Recycle Plastics}*3 + (1 - \text{Recycle Plastics})*5]*\text{Plastics} \quad (16)$$

$$\text{Social Cost Metals} = [\text{Recycle Metals}*3 + \text{Incinerate}*4 + (1 - \text{Recycle Metals} - \text{Incinerate})*5]*\text{Metals} \quad (17)$$

$$\text{Social Cost Yard/Food} = [\text{Compost Yard/Food}*2 + \text{Incinerate}*4 + (1 - \text{Compost Yard/Food} - \text{Incinerate})*5]*\text{Yard/Food} \quad (18)$$

Value Modeling. The model captures the values: the waste diversion from landfill disposal, the economic cost and the social cost for each possible solid waste strategy. The EM would be interested in implementing the strategy that incorporates the largest landfill reduction along with the lowest economic and social costs.

The **Waste Diversion** node captures the total amount of waste diverted from the landfill. This equals the sum of the waste diversions for the particular solid waste strategy, as shown in Equation 19.

$$\begin{aligned}\text{Total Waste Diversion} = {} & \text{Waste Diversion Paper} + \text{Waste Diversion Glass} + \text{Waste Diversion Plastics} \\ & + \text{Waste Diversion Metals} + \text{Waste Diversion Yard/Food} \qquad (19)\end{aligned}$$

The **Economic Cost** node captures the total economic cost for the solid waste strategy. The total economic cost is the sum of the economic costs for the five different waste streams, as shown in Equation 20.

$$\begin{aligned}\text{Total Economic Cost} = {} & \text{Economic Cost Incinerate} + \text{Economic Cost Paper} + \text{Economic Cost Glass} \\ & + \text{Economic Cost Plastics} + \text{Economic Cost Metals} \\ & + \text{Economic Cost Yard/Food} + \text{Economic Cost Composting} \\ & + \text{Economic Cost Recycling} \qquad (20)\end{aligned}$$

The **Social Cost** node captures the total social cost for the solid waste strategy. The total social cost is the sum of the social costs for the five different waste streams, as shown in Equation 21.

$$\text{Total Social Cost} = \text{Social Cost Paper} + \text{Social Cost Glass} + \text{Social Cost Plastics} + \text{Social Cost Metals} + \text{Social Cost Yard/Food} \tag{21}$$

Utility. In order to relate factors with different units of measurement and to provide a way to model the decision makers preferences, utility functions will convert the values into utiles. A utility function incorporates the decision makers preferences and attitude toward risk (Clemen, 1991:361).

The **Diversion Utility** node converts the strategy's total waste diversion into a unitless quantity. Since the model finds the maximum expected value, zero waste diversion is assigned a utility of zero while 100% diversion is assigned a utility of one. In order to incorporate the EM's preference for meeting the pollution prevention goals, a step function will be used which jumps up when the EM has

met the pollution prevention goal. Figure 2 shows the EM's utility function.

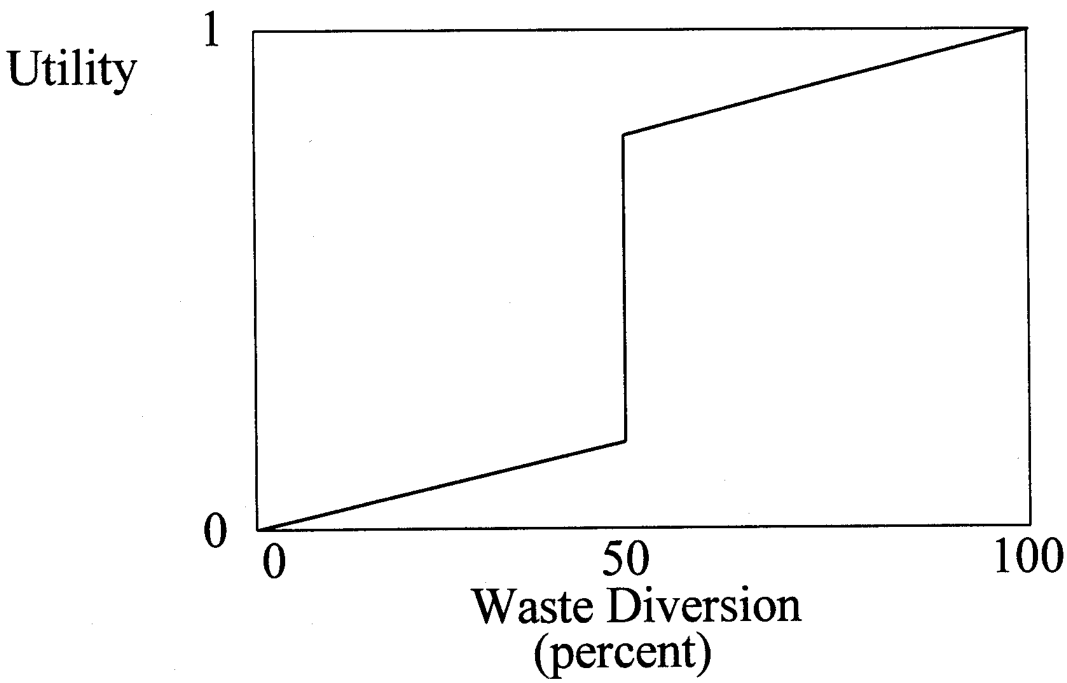

Figure 2. Utility Function for Waste Diversion

Equations 22 and 23 give the Diversion Utility Function.

Diversion Utility (from 0 to <50%) = (Total Waste Diversion/Baseline)*.4 (22)

Diversion Utility (from 50% to 100%) = .6 + (Total Waste Diversion/Baseline)*.4 (23)

The baseline is the point of comparison. In this model, the baseline is the total waste generated in 1992. The baseline can be changed to reflect other points for comparison.

The **Economic Utility** node determines the utility for the economic cost of the strategy. The solid waste strategy with the minimum cost is assigned a utility of one, while the strategy with the maximum cost is assigned a utility of zero. Again, this allows the model to find the largest expected value. This model uses a linear utility function for economic cost. Figure 3 shows the EM's utility function for Economic Cost.

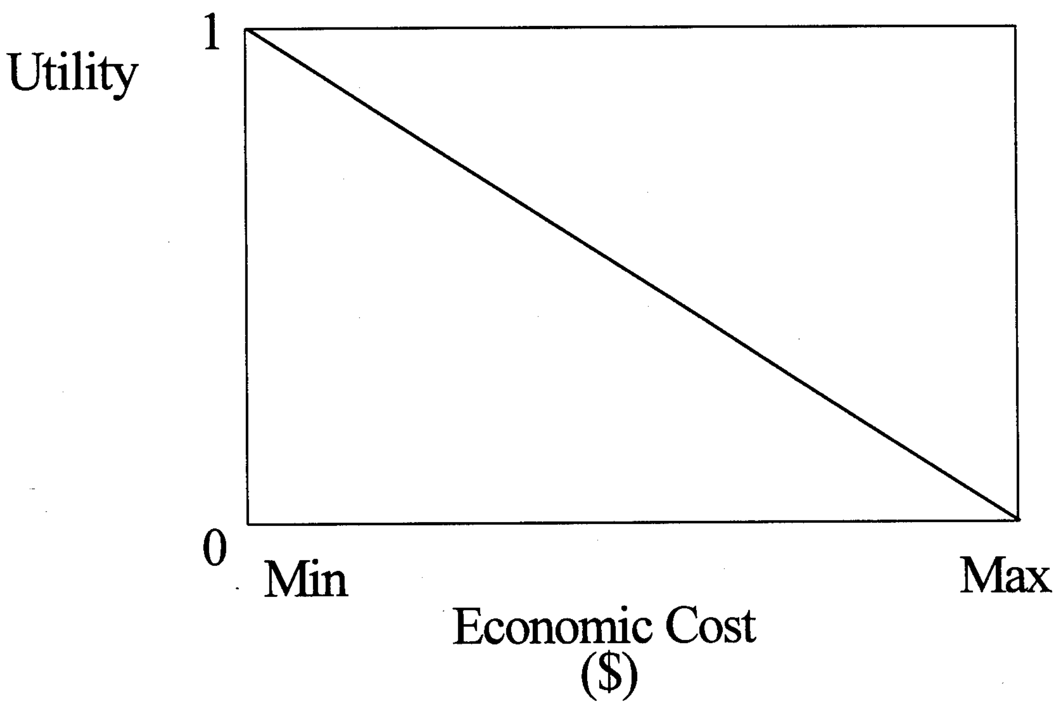

Figure 3. Utility Function for Economic Cost

Equation 24 gives the Economic Utility Function.

$$\text{Economic Utility} = [\text{Max Econ Cost} - \text{Actual Econ Cost}]/[\text{Max Econ Cost} - \text{Min Econ Cost}] \qquad (24)$$

The **Social Utility** node determines the utility for the social cost of the strategy. In order to maximize the expected value, the solid waste strategy with lowest social cost is assigned a utility of one, while the strategy with the largest social cost is assigned a utility of zero. This model uses a linear utility function for social cost. Figure 4 shows the EM's utility function for Social Cost.

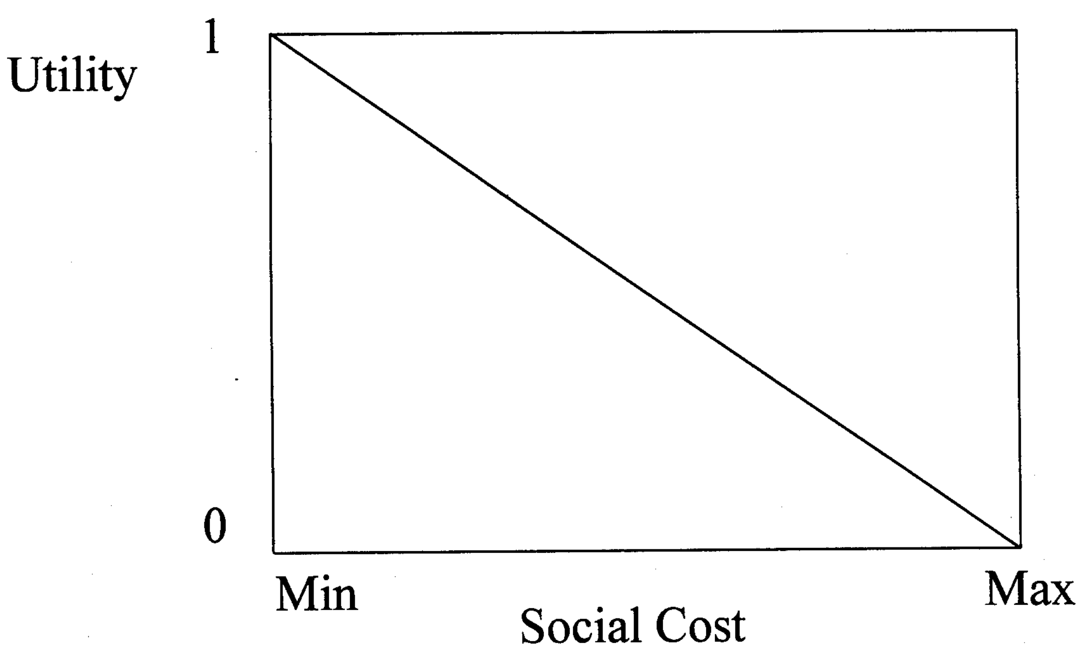

Figure 4. Utility Function for Social Cost

Equation 25 gives the Social Utility Function.

$$\text{Social Utility} = [\text{Max Social Cost} - \text{Social Cost}]/[\text{Max Social Cost} - \text{Min Social Cost}] \qquad (25)$$

The overall **Value** node captures the preferences of the EM. Overall value is the perceived worth to the EM given the values for **Diversion Utility, Economic Utility,** and **Social Utility.** This is shown in Equation 26, where α is the preference factor for diverting waste from the landfill, β is the preference factor for minimizing economic cost, γ is the preference factor for minimizing social cost, and $\alpha + \beta + \gamma = 1$.

$$\text{Value} = \alpha * \text{Diversion Utility} + \beta * \text{Economic Utility} + \gamma * \text{Social Utility} \qquad (26)$$

For example, if the EM were twice as concerned about economic costs as waste diversion and social costs, α would equal 0.25, β would equal 0.5 and γ would equal .25. If the EM were equally concerned about waste diversion and economic costs, but didn't care about social costs, α would equal 0.5, β would equal 0.5 and γ would equal 0.

The EM's preferences are modeled in the **Decision Maker Uncertainty** node. Here, the EM can enter his/her preferences for waste diversion, economic costs, and social costs in order to determine the desired strategy. The EM can also modify his/her preferences to see how that affects the strategy selected.

IV. Analysis and Findings

Introduction

The purpose of the decision support model for municipal solid waste management at Department of Defense Installations is to provide the Environmental Manager with an effective means of identifying which solid waste management strategy is the best for his/her particular situation. To identify the optimum decision and provide additional insight, this thesis relies upon DPL to assist with the quantitative analysis of the decision support model. DPL is a software package specifically designed for building, analyzing, and conducting sensitivity analysis of decision problems (DPL, 1992:2).

Since the solid waste management model is installation-specific, values for a representative installation were used to verify the decision support model and provide the EM with additional insight about the alternative processes. The set of input parameters is defined based upon the MSW at Wright-Patterson AFB, Ohio. The input parameters include waste generation data, costs for disposal, and market buy-back prices for the materials.

Wright-Patterson AFB is one of the largest bases in the Air Force encompassing over 8000 acres. Wright-Patterson has over 1600 facilities on base and employs over 24,000 military and civilians. In addition, there are 2,365 military family housing units on base.

This chapter first describes the types of analysis conducted on the model and the type of information this analysis can provide. In the next section, the notional case values used to verify the model are defined. The last section describes the results of the analysis.

Types of Analysis

Two types of analysis were performed on the decision support model. Decision Analysis, the first type, was performed to identify the optimum decision policy. Value Sensitivity Comparison was performed to determine what effect changes in a variable would have on the final strategy selection and overall utility.

The Decision Analysis first calculates the expected value and identifies the optimal decision policy. The Cumulative Risk Profile is also available as a result of the analysis (DPL, 1992:303). DPL determines the expected value

(DPL, 1992:303) using a process similar to rolling back a decision tree. A Decision Policy chart is available that displays the values and computed outcomes for each decision alternative and identifies the optimum decision alternative for each decision event (DPL, 1992:306). The optimum decision alternative is the decision alternative with the greatest expected utility.

The Value Sensitivity Comparison function identifies which variables have the greatest effect on the final outcome by calculating the expected value as one particular variable ranges in value while all the other variables remain constant (Clemen, 1991:116). The results are then displayed in a tornado diagram format (DPL, 1992:345). Tornado diagrams show how much the value of an alternative can vary with changes in the quantity of a specific variable (Clemen, 1991:116). It is important to know which variables can change the decision. By gaining as much information about them as possible, the best decision can be made.

Notional Case

As stated previously, data from Wright-Patterson AFB is used to verify the model. Table 1 shows the solid waste

generation data from Wright-Patterson AFB. Table 2 lists the variable names and notional values for the waste streams, costs, and prices used in the model along with their units. Table 3 lists the notional objective function variable values, variable names, and definitions. In this scenario, the EM prefers diverting waste from the landfill twice as much as minimizing economic and social costs. Therefore $\alpha = 0.5$, $\beta = 0.25$ and $\gamma = 0.25$.

In Table 2, the notional value for paper includes high-grade, mixed, and low-grade paper as well as newspaper from Table 1. The notional value for metals includes aluminum cans, steel cans, ferrous metals and nonferrous metals from Table 1. The notional value for yard/food waste uses the value for "other" wastes in Table 1.

In Table 3, the Max Social Cost and Min Social Cost are calculated according to Equations 27 and 28.

$$\text{Max Social Cost} = [\,5*1*5519 + 5*1*475 + 5*1*906 + 5*1*2318 + 5*1*1090]/10308 = 5 \tag{27}$$

$$\begin{aligned}\text{Min Social Cost} = \ &[(1*.2 + 2*.3 + 3*.3 + 4*.2 + 5*0)*5519 + (3*.3 + 4*.2 + 5*.5)*475 \\ &+ (3*.3 + 5*.7)*906 + (3*.3 + 4*.2 + 5*.5)*2318 \\ &+ (2*.3 + 4*.2 + 5*.5)*1090]/10308 = 3.28\end{aligned} \tag{28}$$

The Max Social Cost corresponds to landfilling 100 percent of the waste generated. The Min Social Cost is found by incinerating 20 percent of the paper, glass, metals, and yard/food waste in addition to pursuing the maximum source reduction, composting, and recycling.

Table 1

Summary of Wastes Generated at Wright-Patterson AFB in CY 1992 (ton/yr)

Waste	**Base Total**
High-grade paper	2,256
Mixed- and low-grade paper	2,625
Newspaper	638
Cardboard	3,644
Wood	920
Aluminum cans	416
Steel cans	266
Glass	475
Plastics	906
Food	801
Tires	161
Other	1,090
Ferrous metals	1,275
Nonferrous metals	361
Total	15,832

Table 2

Notional Values

Variable Name	**Value**	**Definition/ Units**
Paper	5,519	Tons/yr
Glass	475	Tons/yr
Plastics	906	Tons/yr
Metals	2,318	Tons/yr
Yard/Food	1,090	Tons/yr
Recycling Capital Cost	100,000	Dollars
Composting Capital Cost	40,000	Dollars
Present Landfill Cost	45	Dollars/Ton
Source Reduction Cost	10	Dollars/Ton
Compost Cost	13	Dollars/Ton
Recycling Cost	25	Dollars/Ton
Incineration Cost	39	Dollars/Ton
Paper Price*	140	Dollars/Ton
Glass Price*	20	Dollars/Ton
Plastics Price*	30	Dollars/Ton
Metals Price*	100	Dollars/Ton
Compost Price*	70	Dollars/Ton

*Buy Back Prices from Waste Age's Recycling Times, 19 September 1995:8-9.

Table 3

Notional Objective Function Values

Variable Name	Value	Definition
Waste Total	10,308	Tons/yr
Max Economic Cost	525,871	Maximum Cost Possible (Dollars)
Min Economic Cost	121,562	Minimum Cost Possible (Dollars)
Max Social Cost	5.00	unitless
Min Social Cost	3.28	unitless
Diversion Wt	0.50	Preference for Waste Diversion
Economic Wt	0.25	Preference for Minimizing Economic Costs
Social Wt	0.25	Preference for Minimizing Social Costs

Analysis and Findings of the Base Decision Model

Decision Analysis of the Notional Case. After all the notional values were input into the decision model, a Decision Analysis was performed to identify the optimum decision policy. The Policy Profile, as shown in Figures 5, 6, and 7, implies the EM should change from the current solid waste strategy and pursue a strategy that incinerates 20 percent of the waste. In addition, source reduction, composting and recycling should be pursued to their maximum.

This strategy has an annual economic cost of $131,434 versus $388,073 for the current strategy. The social cost is 3.28 compared to 4.64 for the current strategy. The waste diversion in this case is 70.5% compared to 17.9% for the current strategy.

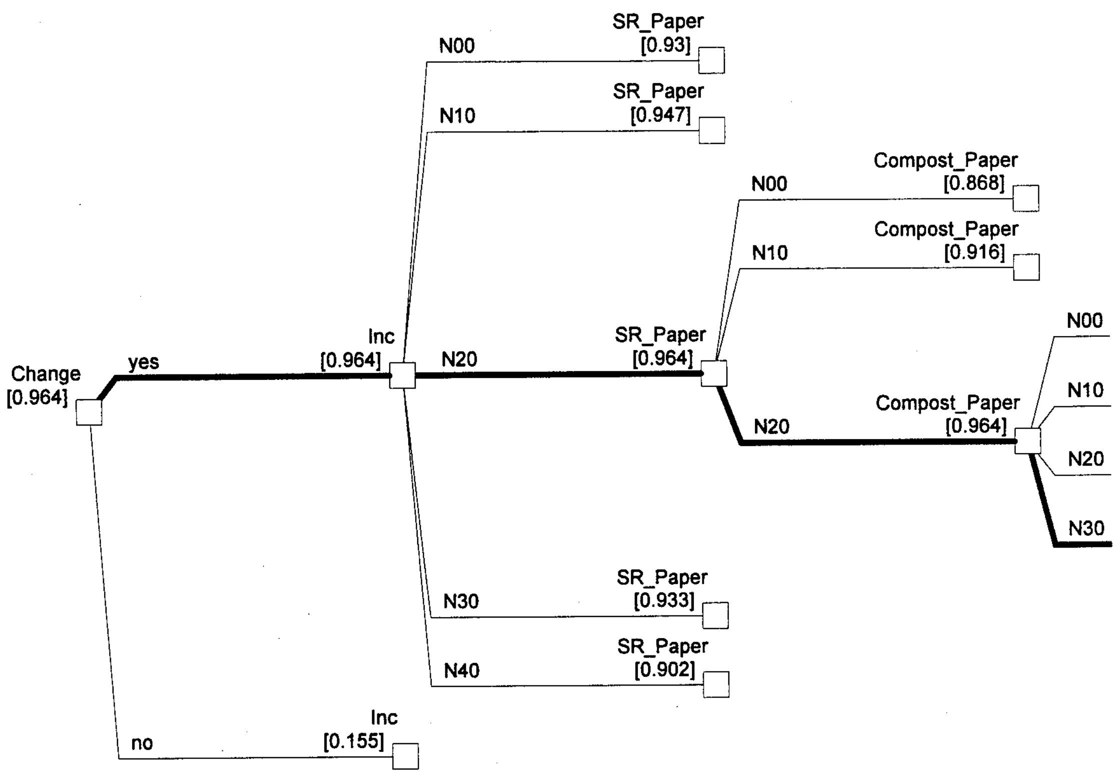

Figure 5. Optimal Decision Policy of Notional Case.

Figure 5 shows a change should be made that incorporates incineration at 20 percent, and source reduction of paper at 20 percent.

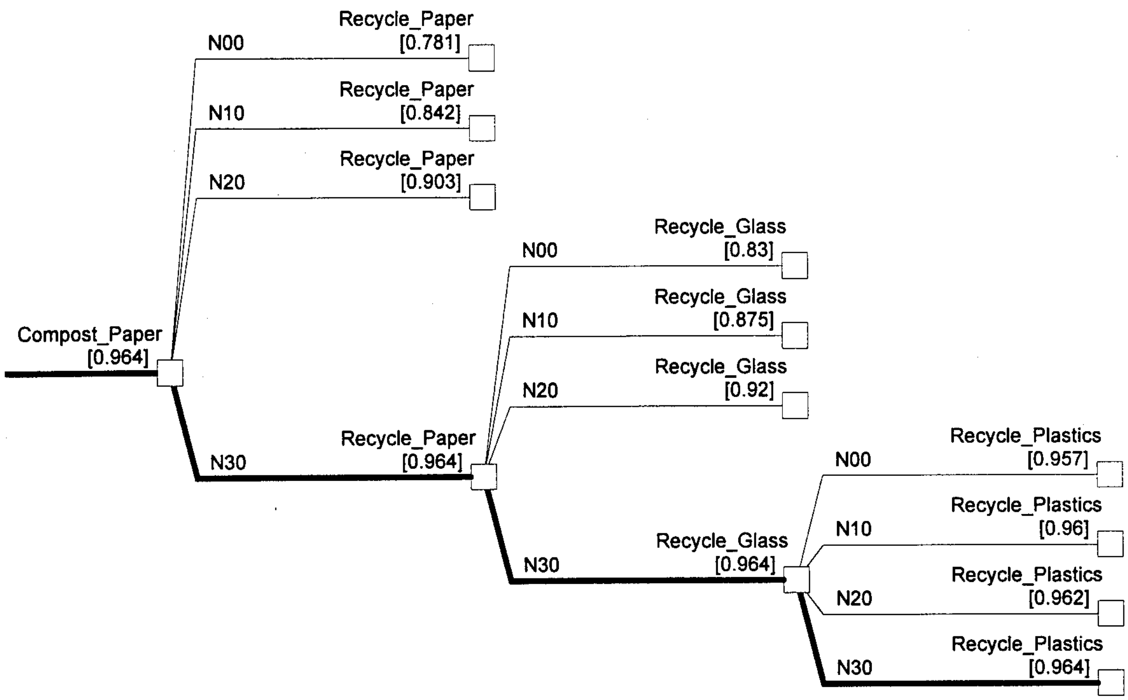

Figure 6. Optimal Decision Policy of Notional Case.

Figure 6 shows composting paper at 30 percent, recycling paper at 30 percent, and recycling glass at 30 percent. Figure 7 shows recycling plastics at 30 percent, recycling metals at 30 percent, and composting yard/food waste at 30 percent.

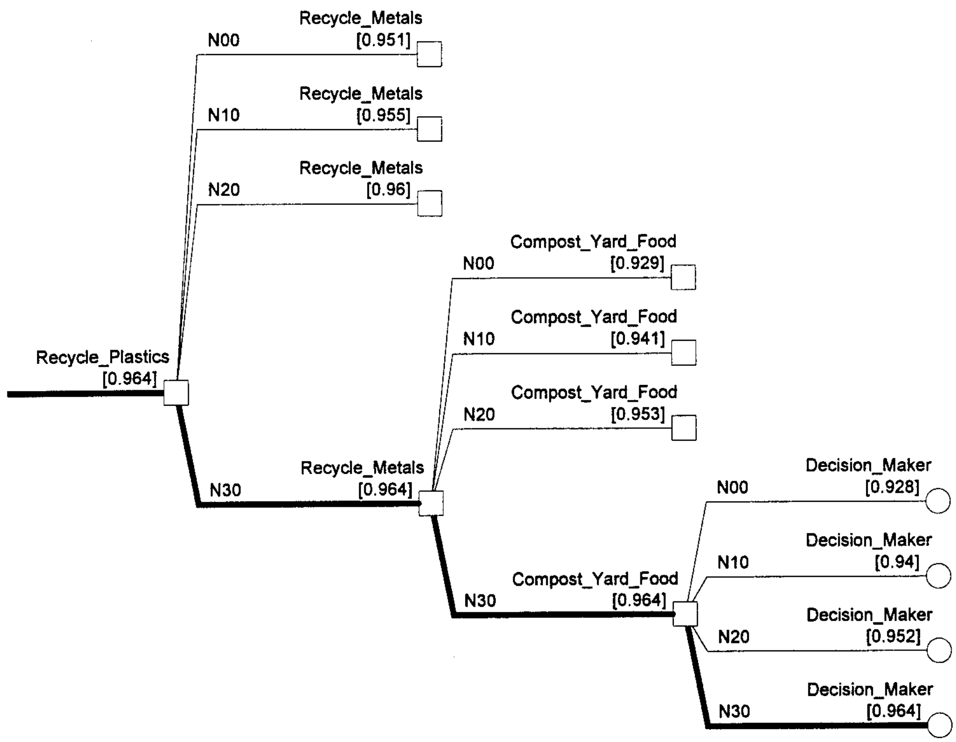

Figure 7. Optimal Decision Policy of Notional Case.

<u>Value Sensitivity Comparison of Notional Case.</u> In order to determine the effect a variable has on the expected value as the variable ranges in value, value sensitivity comparisons were conducted and the results tabulated in a tornado diagram.

Figure 8 shows the tornado diagram derived from the value sensitivity comparison of the notional variables. In this type of chart, the width of the bar reflects the effect

on the expected utility as the value of the chosen variable is varied. The variables at the top of the diagram have the greatest effect on the final outcome. A variable whose associated bar changes shading indicates the decision policy changes as the value of the variable changes.

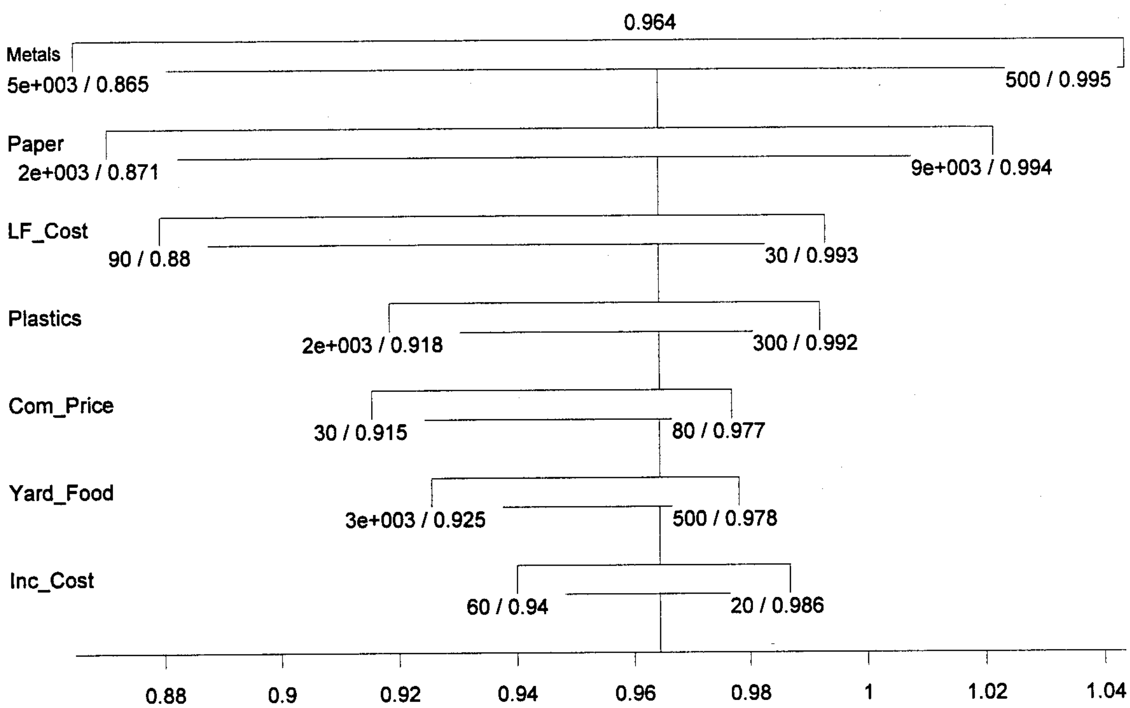

Figure 8. Value Sensitivity Comparison in the Notional Case.

For this model, Figure 8 shows the seven variables that have the greatest impact on the expected utility. Four of the variables are the waste streams while the other three are the landfill cost ($/ton), the compost purchase price

($/ton), and the incineration cost ($/ton). These variables have the greatest impact on the expected utility, but when all other variables remain the same, the decision policy does not change.

Table 4

Strategy Comparison Table

	Strategy	**Economic Cost ($)**	**Social Cost**	**Waste Diversion (tons)**	**Expected Utility**
1	100% Landfill	463,860	5.00	0	0.038
2	Baseline	388,073	4.64	1,844	0.155
3	100% Incineration then Landfill	513,221	4.09	7,052	0.608
4	90% Incineration and Max Diversion	490,375	3.83	7,558	0.645
5	80% Incineration and Max Diversion	450,182	3.62	7,793	0.661
6	70% Incineration and Max Diversion	310,646	3.57	**8,028**	0.818
7	60% Incineration and Max Diversion	286,394	3.45	7,875	0.850
8	50% Incineration and Max Diversion	262,141	3.32	7,722	0.881
9	40% Incineration and Max Diversion	218,572	3.31	7,569	0.902
10	Max Diversion without Incineration	**121,562**	3.46	5,852	0.930
11	30% Incineration and Max Diversion	175,003	3.29	7,415	0.933
12	10% Incineration and Max Diversion	126,498	3.37	6,557	0.947
13	20% Incineration and Max Diversion	131,434	**3.28**	7,262	**0.964**

Strategy Comparison

Table 4 shows a comparison of some of the various waste management strategies and their values for economic cost, social cost and waste diversion. These values are for the original notional case.

As shown in the above table, based on the preferences established earlier for the EM, the preferred strategy in this case is to incinerate 20 percent of paper, glass, metals, and yard/food waste while maximizing source reduction, composting, and recycling efforts. This strategy has the least social cost. The maximum diversion without incineration strategy has the least economic cost. The 70 percent incineration strategy achieves the greatest waste diversion from the landfill.

Strategy 13 dominates strategies 1, 2, and 3 since strategy 13 has a lower economic cost, lower social cost, and greater waste diversion. Strategy 6 dominates strategies 4 and 5 since it has a lower economic cost, lower social cost, and greater waste diversion.

There is no dominating strategy. Strategies 6 through 13 are the only non-dominated strategies. The decision

maker's preferences will determine which strategy to implement.

Decision Analysis

Table 5 shows the change in economic cost, social cost, and waste diversion that can be achieved through strategy 13 by increasing the maximum rate of one of the waste management decisions by 10 percent. For example, if recycling metals is increased from 30 to 40 percent, the waste management strategy has an economic cost of $126,798, a social cost of 3.23, and a waste diversion of 7,494 tons.

Table 5

Decision Comparison Table

	Economic Cost ($)	**Social Cost**	**Waste Diversion (tons)**
SR Paper	-24,253	-0.13	-153
Compost Paper	-57,366	-0.07	-153
Recycle Paper	-43,570	-0.02	-153
Recycle Glass	-950	-0.01	+48
Recycle Plastics	-1,812	-0.02	+91
Recycle Metals	-4,636	-0.05	+232
Compost Yard/Food	-10,355	-0.04	+109

For strategy 13 with 40 percent metals recycling, Table 5 shows a decrease in economic cost of $4,636, a decrease in social cost of 0.05, and an increase in waste diversion of 232 tons.

Table 5 shows that even greater economic savings and waste diversion are possible at a lower social cost. The EM can decide which decision to pursue in order to achieve economic, social, or waste diversion goals. If the EM wants to reduce economic costs, the rate of composting paper should be increased. If reducing social costs is the goal, an increase in the source reduction of paper should be pursued. Finally, if waste diversion is to be increased, the best alternative in this case is to increase the recycling rate of metals.

V. Conclusions and Recommendations

Overview

The primary objective of this thesis is to provide the installation Environmental Manager with a tool to identify the preferred strategy for managing the installation's municipal solid waste. To accomplish this objective, this thesis created and verified a decision support model utilizing the DPL software package. The decision support model was created by modeling the structure and preferences of the decision problem. The overall value for the strategy was based on the strategy's economic cost, social cost, waste diversion from the landfill, and the EM's preferences.

After the decision support model was developed, a comprehensive analysis was performed using actual municipal solid waste data from Wright-Patterson AFB. The optimum decision policy was determined and sensitivity analysis was performed to provide additional insight for the decision maker.

Summary of Findings

Several conclusions about the model can be drawn from the results of the scenario used to test and validate the model. First, there are numerous waste management strategies with a higher expected utility than the baseline waste management strategy. The model provides the EM with the support necessary to pursue additional research into the alternatives for municipal solid waste management.

The best waste management strategy has an expected utility of 0.964, while the baseline strategy has an expected utility of 0.155. This best strategy sends 20 percent of the paper, glass, metals, and yard/food waste to the incinerator. In addition, the source reduction rate for paper is 20 percent, the composting rate is 30 percent for paper and yard/food waste, and the recycling rate is 30 percent for paper, glass, plastics, and metals.

Second, the model demonstrates that maximizing source reduction, composting, and recycling efforts when possible is preferred to landfilling in all cases. Even where incineration is selected, it is preferred to divert as much waste as possible from the landfill.

Third, the EM that is strictly interested in diverting waste from the landfill will have to consider an incineration strategy. Incineration alone will not achieve the greatest waste diversion, but must be combined with source reduction, composting, and recycling. Pursuing an incineration strategy will provide the greatest waste diversion from the landfill, but only with increased economic and social costs.

Future Research

The decision support model for municipal solid waste management is very useful in its present form. The EM can use the model to determine the preferred waste management strategy based on his/her particular situation. In addition, the EM can use the model to determine the economic cost, social cost, and waste diversion for the present strategy as well as any other selected strategy in between.

Future research is needed to adapt the model for use with more common software. Although, DPL is not in widespread use by Environmental Managers, it can be linked to Excel to make it more user-friendly.

In its current form, the decision support model uses specific utility functions to model the risk attitudes of the EM for the three values: economic cost, social cost, and waste diversion. Future research could modify the utility functions to see how the decision changes based on a change in the EM's risk attitude.

The current model was applied with values from Wright-Patterson AFB. Future research could verify the model with data from other Department of Defense Installations.

Future research could also expand the model to include more specific composting and recycling alternatives. One option may be to include transporting waste to off-base composting sites. Separate recycling collections in base housing may be evaluated against voluntary drop-off programs.

Future research could also expand the model to include more than the five waste streams used in this model. Yard and food waste could be considered separately. Metals could be broken out into aluminum cans, steel, and scrap metal. More common items found at military installations, such as wood pallets and tires, could be included as well.

The decision analysis principles used in this research proved worthwhile in comparing and evaluating the economic cost, social cost, and waste diversion associated with each strategy. These principles could be effectively applied to other waste management disciplines such as hazardous, radioactive, or nuclear waste.

Appendix

Decision Analysis Theory

Decision analysis gives decision makers a means to better understand the problems they face. That understanding includes the structure of the problem as well as the uncertainty and trade-offs inherent in the alternatives and outcomes. Decision analysis is an information source that provides insight about the situation, uncertainty, objectives and tradeoffs along with a recommended course of action (Clemen, 1991:4). The overall strategy of decision analysis is to decompose a complicated problem into smaller elements that are more easily understood and analyzed (Clemen, 1991:9).

The first step is to identify and elements of the problem. These can be classified as decisions to make, uncertain events, and the values of specific outcomes (Clemen, 1991:17).

The decision maker has complete control over the decisions to make (Clemen, 1991:17). For example, in the case of the farmer, the farmer may take protective actions now to save the crop from possibly bad weather, decide to do

nothing, or wait before making his decision. The farmer may make sequential decisions if he decides to wait. Then he faces the same decision at a later date.

Uncertain events are factors that affect the final outcome of the decision problem. Uncertain events are beyond the control of the decision maker (Clemen, 1991:19). In the farming example, the key uncertain event is the weather. The farmer has no control over frost or rain yet those events will determine the future value of his crop.

The value of specific outcomes is the final outcome after all the decisions have been made and all the uncertain events are known (Clemen, 1991:21). In the farming example, the value of the specific outcome may be breaking even, a large profit or even a loss.

There are two decision analysis approaches for modeling decision problems: influence diagrams and decision trees. Each are valuable and complement one another nicely (Clemen, 1991:34). An influence diagram provides a visual representation of the decision problem. Decisions are represented by squares. Uncertain events are represented by circles. Values for outcomes are shown as squares with rounded corners (Clemen, 1991:34). These shapes are

referred to as nodes: decision nodes, chance nodes, and value nodes. Nodes are connected by arrows called arcs to show their relationship (Clemen, 1991:34). Influence diagrams suppress many details and are ideal for obtaining an overview of a complex problem (Clemen, 1991:56).

Decision trees, on the other hand, display more of the details that remain hidden in an influence diagram (Clemen, 1991:49). Decision trees display the possible decision alternatives on branches emanating from squares. The possible outcomes of uncertain events are displayed on branches emanating from circles (Clemen, 1991:49). Values are displayed at the end of the last branch.

The next step in modeling a decision problem is to model the uncertainty. Uncertainty can be modeled through an appropriate use of probability (Clemen, 1991:169). Uncertainty can be modeled by using standard mathematical models, historical data, and computer simulation (Clemen, 1991:167). The major uncertainty in this problem will be the actual waste streams. Most installations have a good idea of what their waste is, but they are still uncertain.

The last step in modeling a decision problem is modeling the preferences of the decision maker. Because

most decision problems involve some kind of trade-off, it is necessary to model preferences (Clemen, 1991:361). The solid waste management problem is a multiattribute decision problem with different dimensions of values. In this case, utility will be the unit of measurement. Utility is the perceived worth to the individual decision maker.

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Vita

Captain John F. Muratore was born on January 1, 1969 at Whiteman AFB, Missouri. In 1987, he graduated from Merced High School in Merced, California. In 1991, he graduated cum laude from Santa Clara University in Santa Clara, California with a Bachelor of Science Degree in Mechanical Engineering and received his commission through the Air Force ROTC program. From September 1991 to August 1992, he was assigned to the 31st Civil Engineering Squadron at Homestead AFB, Florida. Following Hurricane Andrew, he was assigned to the 645th Civil Engineer Group at Wright-Patterson AFB, Ohio. He is currently attending the Air Force Institute of Technology as a graduate student in the Engineering and Environmental Management Program. Following graduation, he will be assigned to the 5th Air Force Civil Engineering Staff at Yokota Air Base, Japan.

Permanent Address: 1215 WN Bear Creek Dr.
Merced, California 95348

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13. ABSTRACT *(Maximum 200 words)*

This research focuses on the development of a decision support model to identify the preferred strategy for managing municipal solid waste using the principles of decision analysis theory. The model provides an effective decision making tool to evaluate and compare different municipal solid waste management strategies. The users of this model, the Environmental Manager or decision maker at a given installation, can enter installation-specific waste stream characteristics, treatment and disposal costs, and material buy-back prices to determine the expected value for various alternative strategies. The strategy having the greatest expected value is considered the preferred alternative. In calculating the expected value of a strategy, the economic cost, social cost, and waste diversion from the landfill are evaluated. This research also includes a representative case study to illustrate the use of the decision support model. Although the case study addresses Wright-Patterson AFB, the model can be applied to any Department of Defense Installation.

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